New Flutter Analysis Technique for Time-Domain Computational Aeroelasticity

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Prepared By:
Chan-gi Pak and Shun-fat Lung
Structural Dynamics Group, Aerostructures Branch (Code RS)
NASA Armstrong Flight Research Center

Overview

- Theoretical background (slides 3-6)
- Computational validation (slides 7-18)
- Conclusions (slide 19)

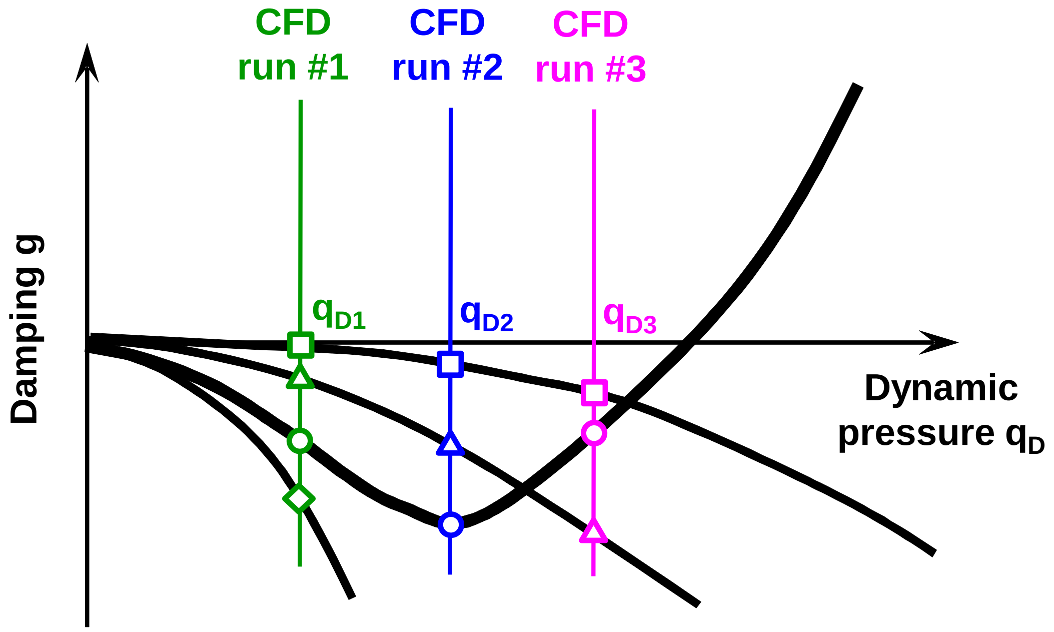
What the technology does

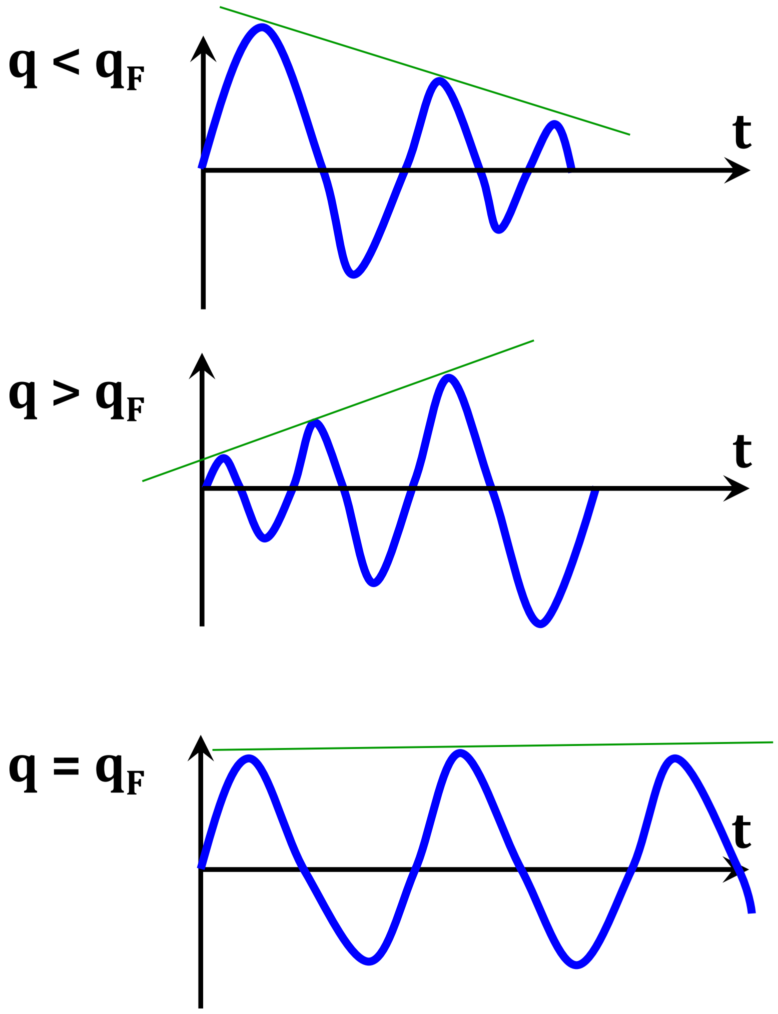
Problem Statement

- The classical method of determining the flutter speed from CFD results is using a time-consuming trial-and-error process.
- Previous technologies provide system damping factors and frequencies at a single dynamic pressure with a single CFD run.

Objective

- Develop a simple efficient approach for flutter speed and frequency prediction



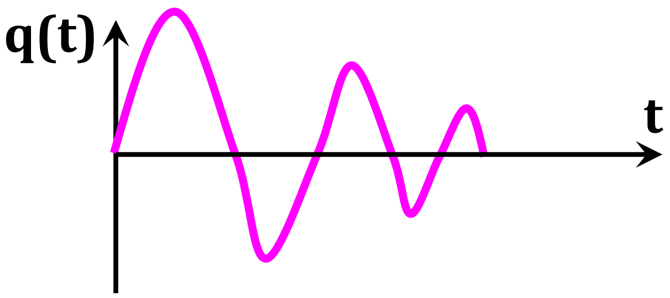


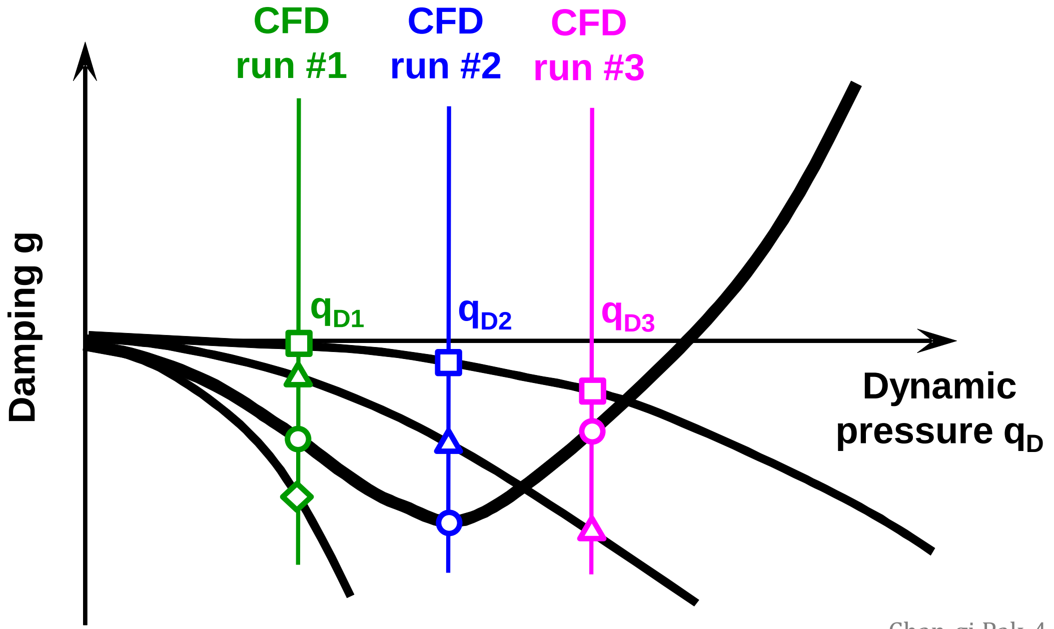
Previous technologies

- Bennett, R. M., and Desmarais, R. N., "Curve Fitting of Aeroelastic Transient Response Data with Exponential Functions," NASA-SP-415, pp. 43-58, 1975.
  - Non-linear least squares fitting

$$q(t) = q_0 + \sum_{i=1}^{nm} e^{-\sigma_i t}\{A_i cos(\omega_{di} t) + B_i sin(\omega_{di} t)\}$$

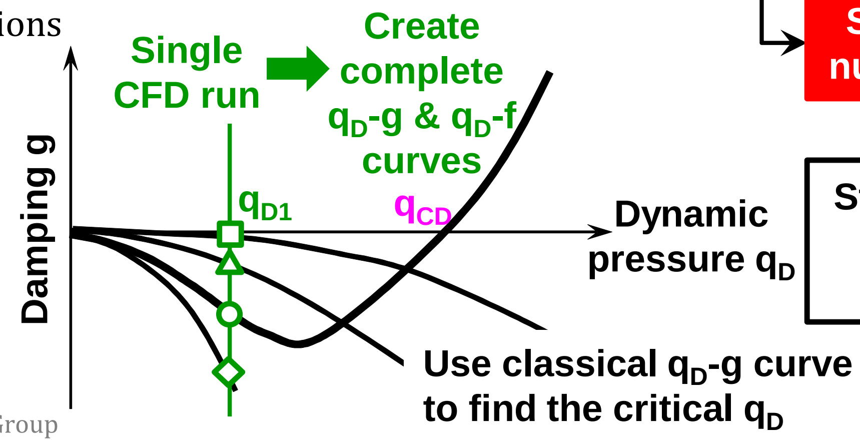
    - Optimization problem; strongly depends on starting damping factor and frequency values
  - Results are system damping factors and frequencies
- Pak, C.-G., and Friedmann, P. P., "New Time Domain Technique for Flutter Boundary Identification," AIAA-92-2102, AIAA Dynamics Specialist Conference, Washington, D.C., 1992.
  - Assume that an aeroelastic (structure + aerodynamic) system is **unknown**.
  - Estimate aeroelastic system matrices using single-input single-output parameter estimation together with ARMA model
  - Compute aeroelastic system damping factors and frequencies

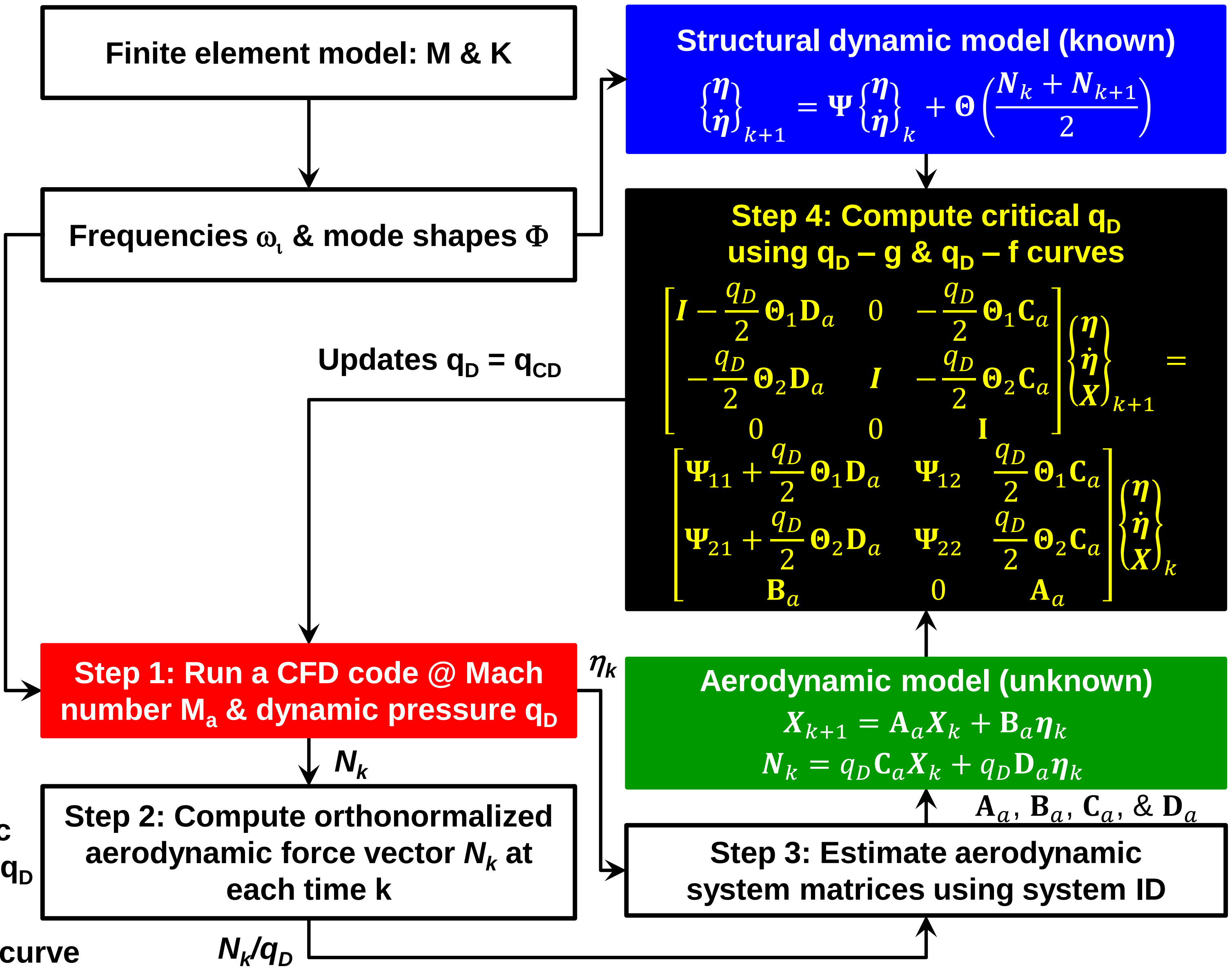




Technical features of new technology

- Approach
  - Structural model is assumed **known**.
  - The unsteady CFD analysis is performed using an **estimated dynamic pressure**, q_D.
    - Use a linear panel code or test data
  - Non-dimensionalize orthonormalized aerodynamic force vector.
  - Estimate **unknown** aerodynamic system matrices, $\mathbf{A}_a$, $\mathbf{B}_a$, $\mathbf{C}_a$, & $\mathbf{D}_a$, using a multi-input multi-output parameter estimation.
    - Multi-input: orthonormalized deflection vector
    - Multi-output: orthonormalized aerodynamic force vector
  - Compute the critical dynamic pressure using the **known** structural model and the **estimated** aerodynamic model.
    - Each iteration solves for the **critical dynamic pressure**, q_D, and uses this value in subsequent iterations





Technical features of new technology (continued)

- Structural dynamic differential equations of motion in matrix form:

$$\mathbf{M}\ddot{\boldsymbol{q}} + \mathbf{C}\dot{\boldsymbol{q}} + \mathbf{K}\boldsymbol{q} = \boldsymbol{Q}$$

- Generalized displacement vector $\boldsymbol{q}$:

$$\boldsymbol{q} \equiv \boldsymbol{\Phi}\boldsymbol{\eta}$$

$\boldsymbol{\Phi}$ =mode shape

$\boldsymbol{\eta}$=orthonormalized coordinate vector

- Orthonormalized differential equations of motion:

$$\ddot{\boldsymbol{\eta}} + 2\boldsymbol{\zeta}\boldsymbol{\omega}\dot{\boldsymbol{\eta}} + \boldsymbol{\omega}^2\boldsymbol{\eta} = \boldsymbol{N}$$

$$\boldsymbol{N} = \boldsymbol{\Phi}^T\boldsymbol{Q}$$

- State differential equation in continuous time t:

$$\begin{Bmatrix}\dot{\boldsymbol{\eta}}\\ \ddot{\boldsymbol{\eta}}\end{Bmatrix} = \boldsymbol{A}\begin{Bmatrix}\boldsymbol{\eta}\\ \dot{\boldsymbol{\eta}}\end{Bmatrix} + \boldsymbol{B}\boldsymbol{N}$$

$$\boldsymbol{A} = \begin{bmatrix} 0 & \boldsymbol{I} \\ -\boldsymbol{\omega}^2 & -2\boldsymbol{\zeta}\boldsymbol{\omega}\end{bmatrix} \quad \boldsymbol{B} = \begin{bmatrix}0\\ \boldsymbol{I}\end{bmatrix}$$

- State difference equation in discrete time k:

$$\begin{Bmatrix}\boldsymbol{\eta}\\ \dot{\boldsymbol{\eta}}\end{Bmatrix}_{k+1} = \boldsymbol{\Psi}\begin{Bmatrix}\boldsymbol{\eta}\\ \dot{\boldsymbol{\eta}}\end{Bmatrix}_{k} + \boldsymbol{\Theta}\left(\frac{\boldsymbol{N}_k + \boldsymbol{N}_{k+1}}{2}\right)$$

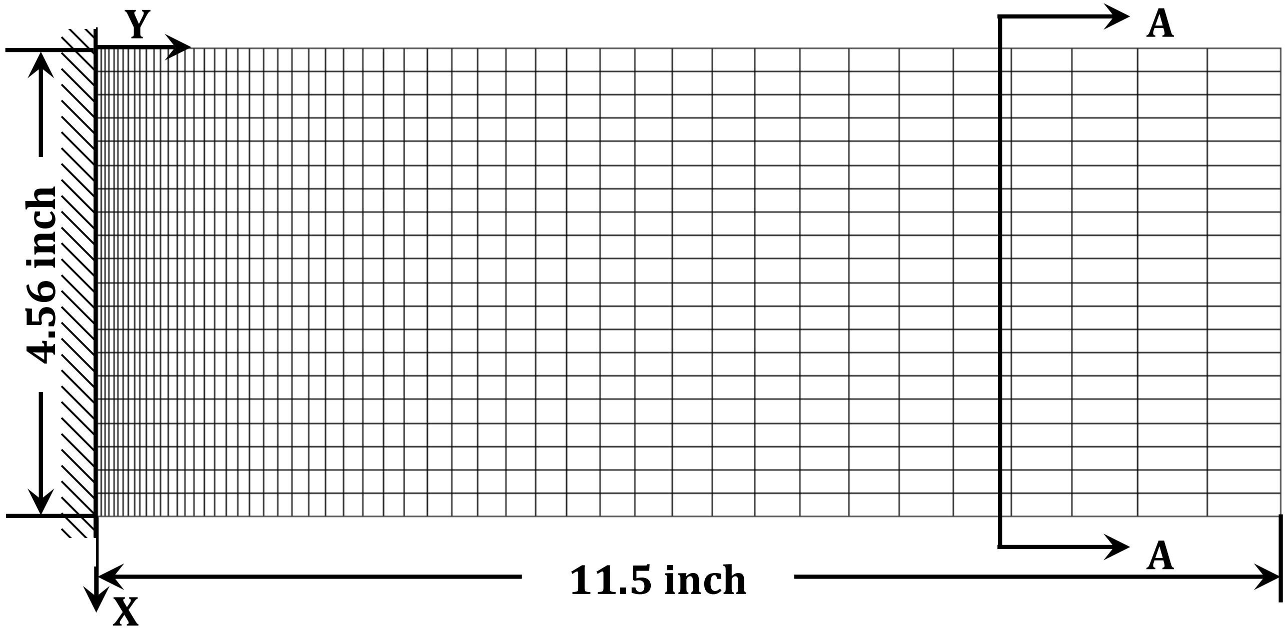
$$\boldsymbol{\Psi} = \mathrm{e}^{\boldsymbol{A}\Delta T} \quad \boldsymbol{\Theta} = \boldsymbol{\Gamma}\,\mathbf{B} \quad \boldsymbol{\Gamma} = \int_0^{\Delta T} \mathrm{e}^{\boldsymbol{A}(\Delta T-\sigma)}\,d\sigma \quad \Delta T = \text{time step}$$

Computational Validation

Cantilevered rectangular wing model

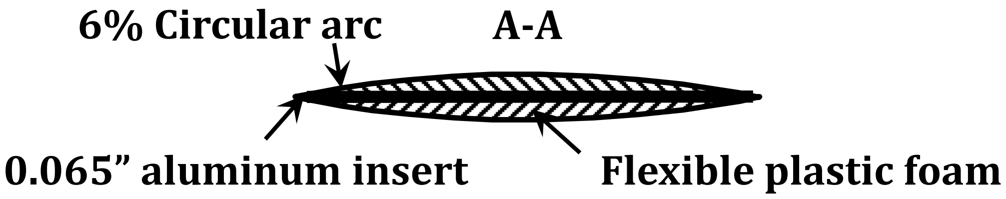
Structural Model & Results from Modal Analysis

- Configuration of a wind tunnel test article
  - Has **aluminum insert** (thickness = 0.065 in) covered with **6% circular arc** cross-sectional shape (**plastic foam**)
  - lumped mass weight are computed based on 6% circular-arc cross sectional shape.
    - Use structural dynamic model tuning technique
    - Chan-gi Pak and Samson Truong, “Creating a Test-Validated Finite-Element Model of the X-56A Aircraft Structure,” *Journal of Aircraft*, Vol. 52, No. 5, pp. 1644-1667, 2015. doi: http://arc.aiaa.org/doi/abs/10.2514/1.C033043
- Modal analysis
  - NASTRAN sol. 103



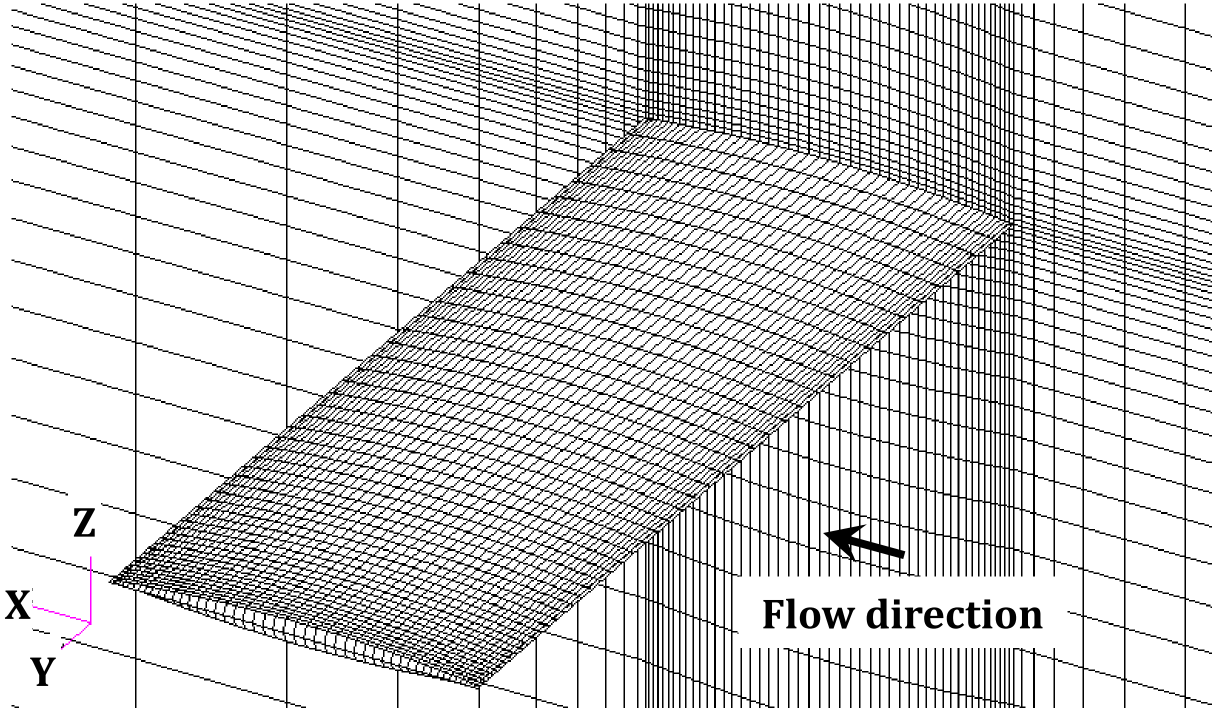
Measured and computed natural frequencies

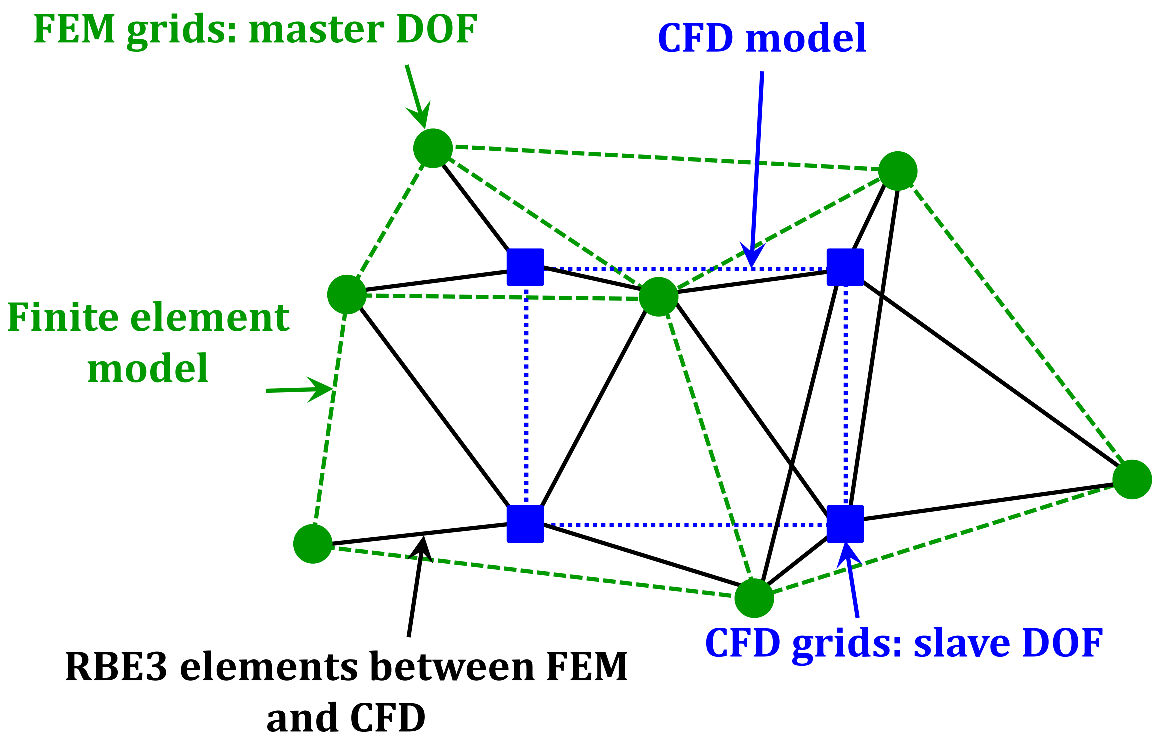
Mode	Measured (Hz)	Computed (Hz)	% Error
1	14.29	14.29	0.0
2	80.41	80.17	-0.3
3	89.80	89.04	-0.8



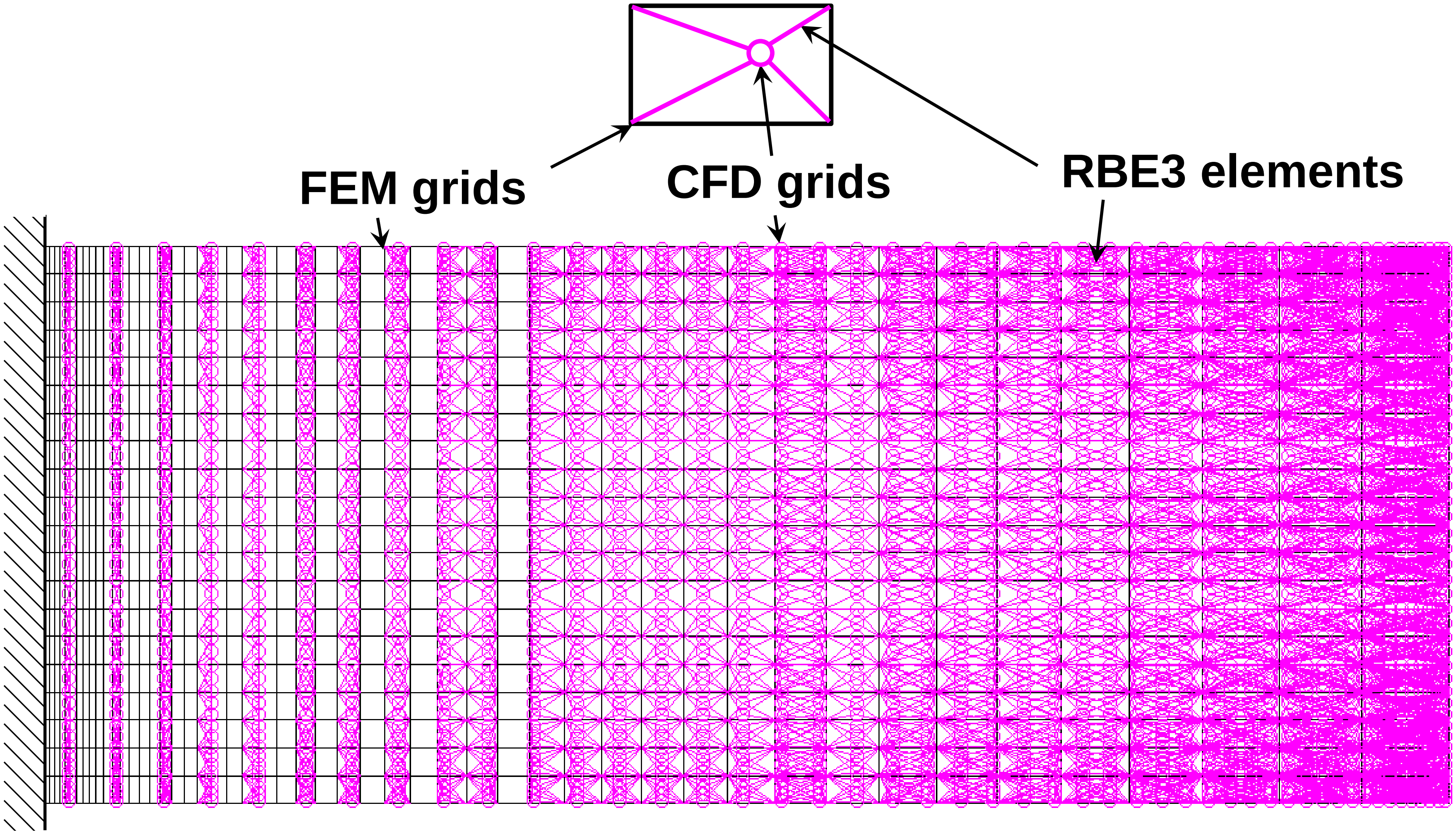
CFL3D model & spline between CFL3D and NASTRAN

- **CFL3D v.6 code** is used.
  - Compute orthonormalized displacement and aerodynamic force vectors.
  - The CFD grid is a multi-block (97 × 73 × 57) grid with H-H topology.
  - The first **three** flexible modes are used.
- **Splines between CFL3D and NASTRAN**
  - Use interpolation element, RBE3, between FE grids and CFD grids.
  - Include CFD grids in structural FE model
    - Structural FEM grids: master DOF
    - Surface CFD grids: slave DOF



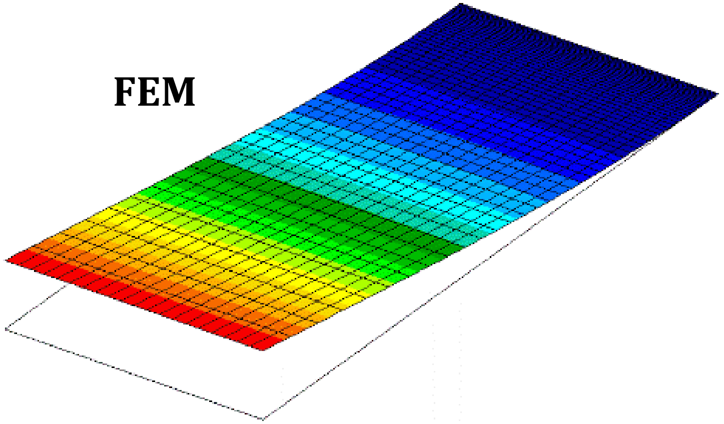


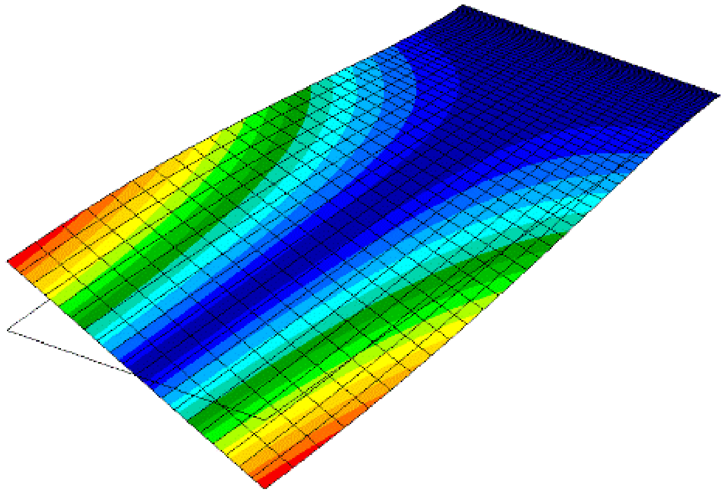
FEM and CFD grids connection using RBE3 elements

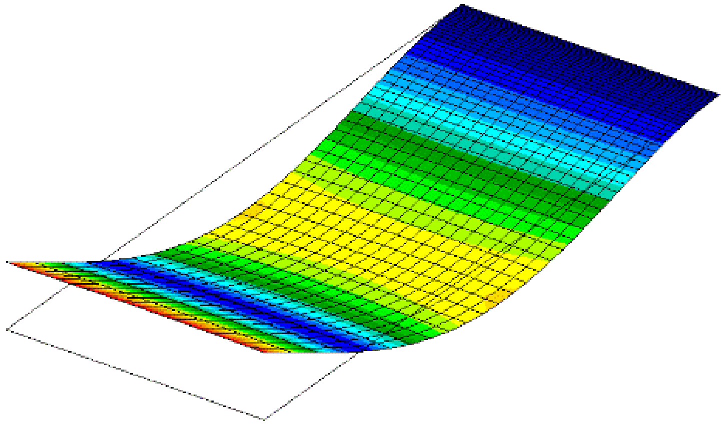


Mode shapes of the cantilevered rectangular wing on structural and aerodynamic models

FEM

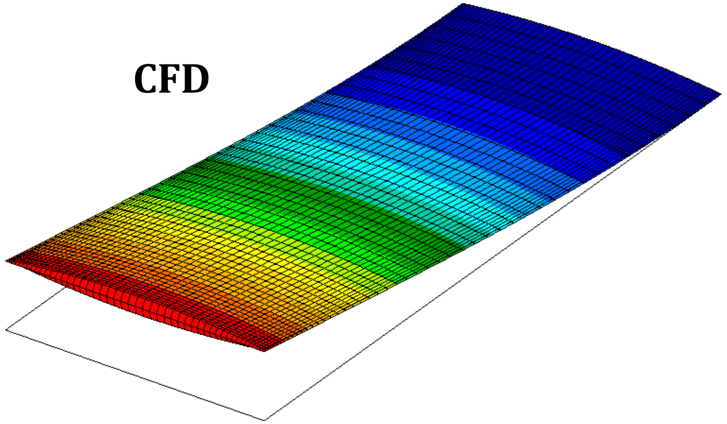


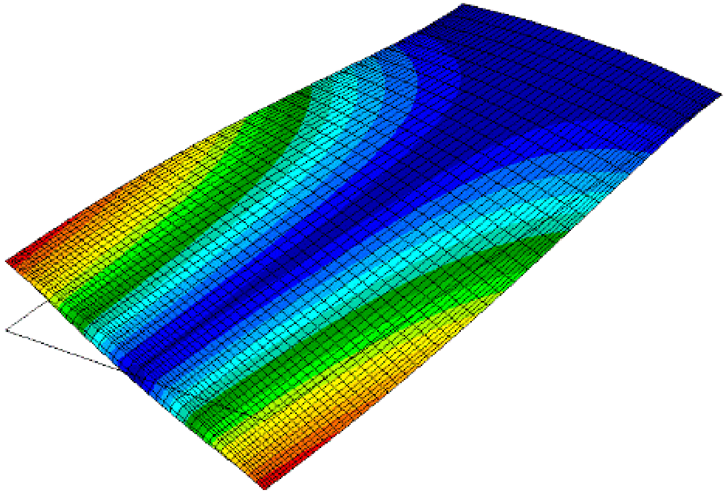


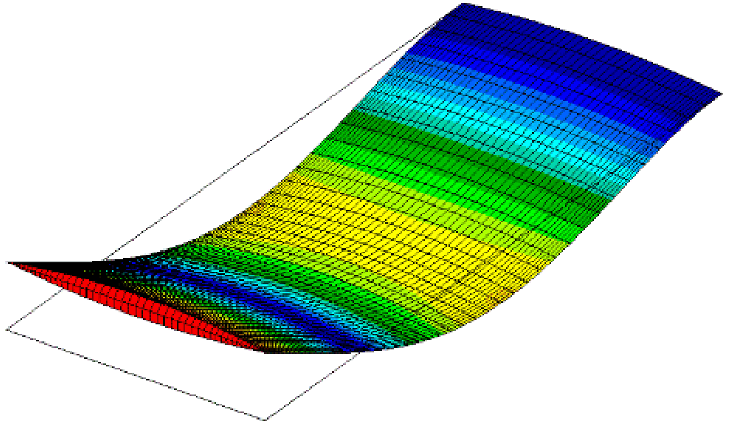


Mode 1 **Mode 2** **Mode 3**

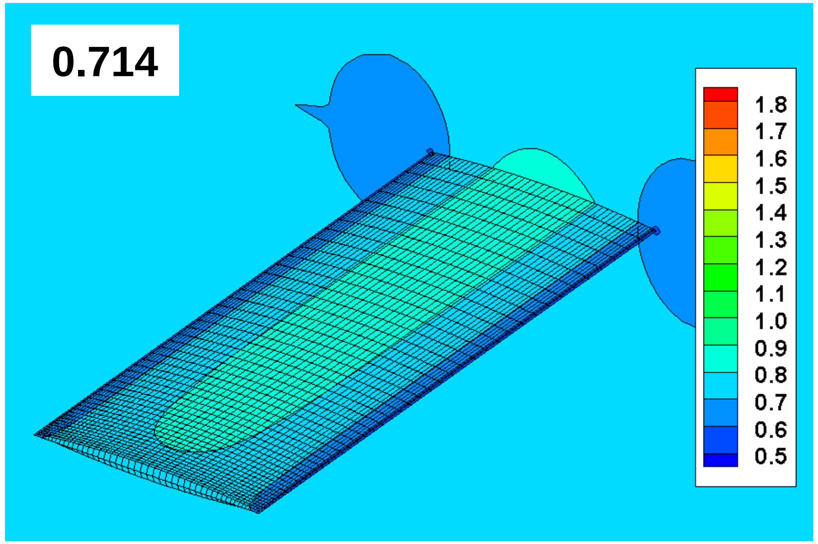
CFD

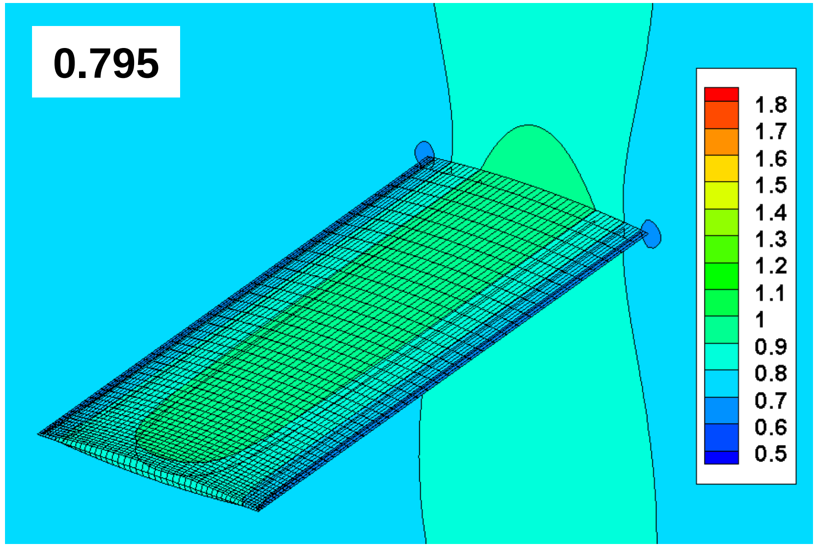


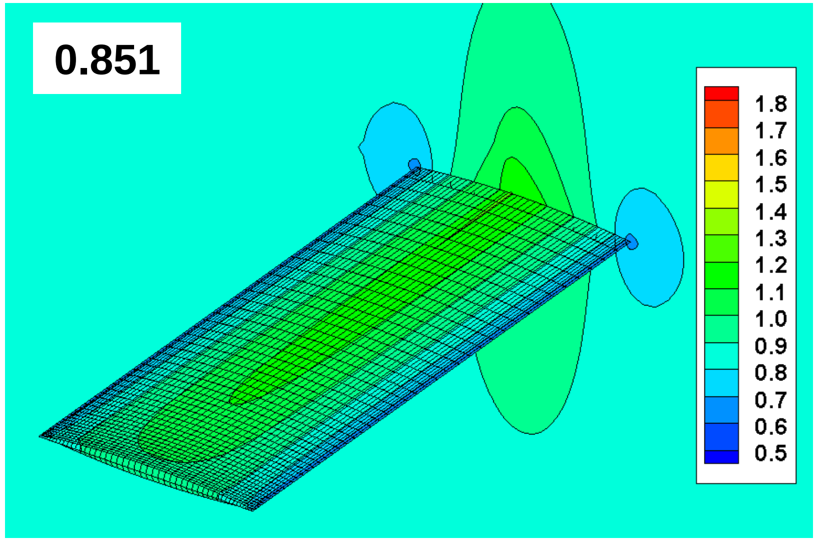


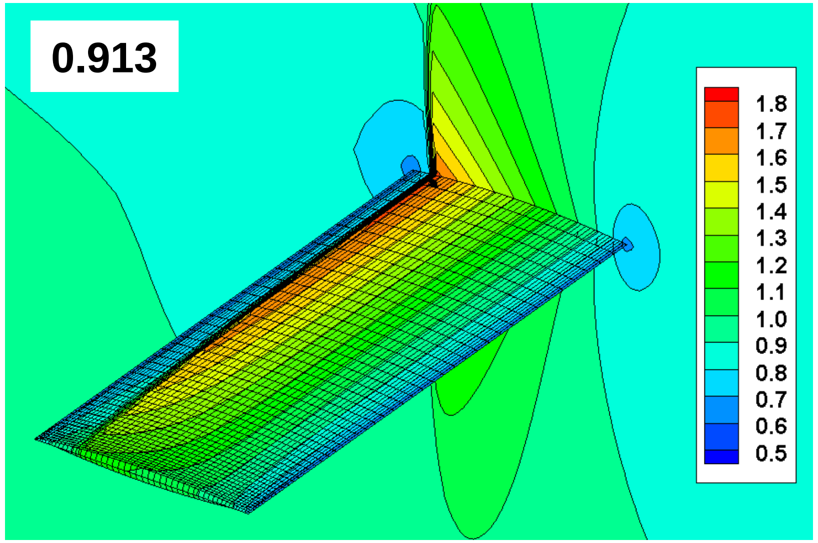


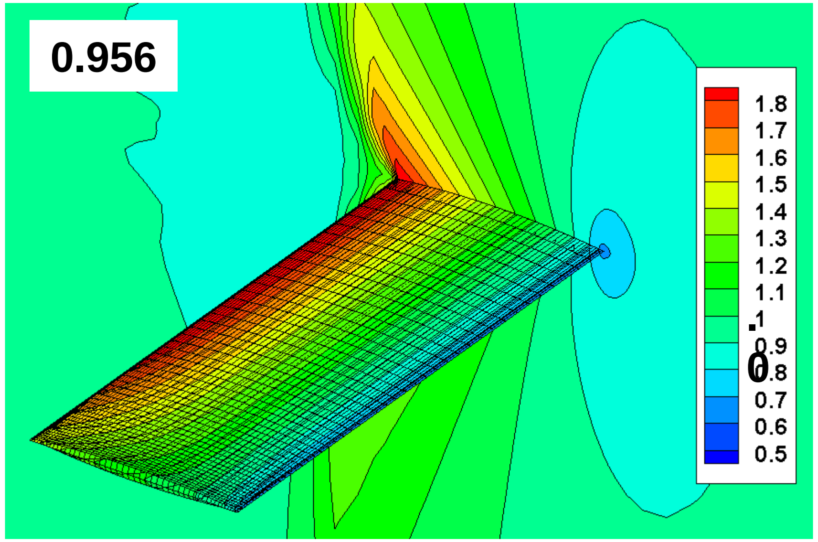
Local Mach number contour from steady CFD computations

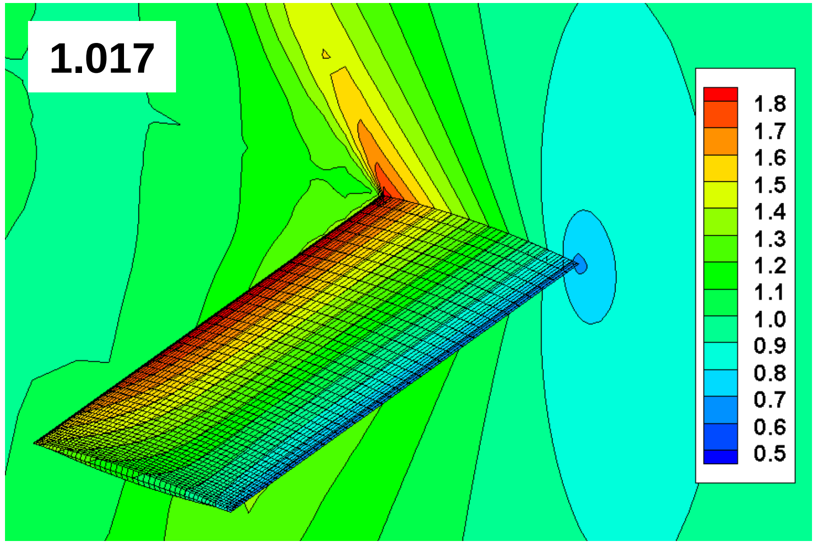




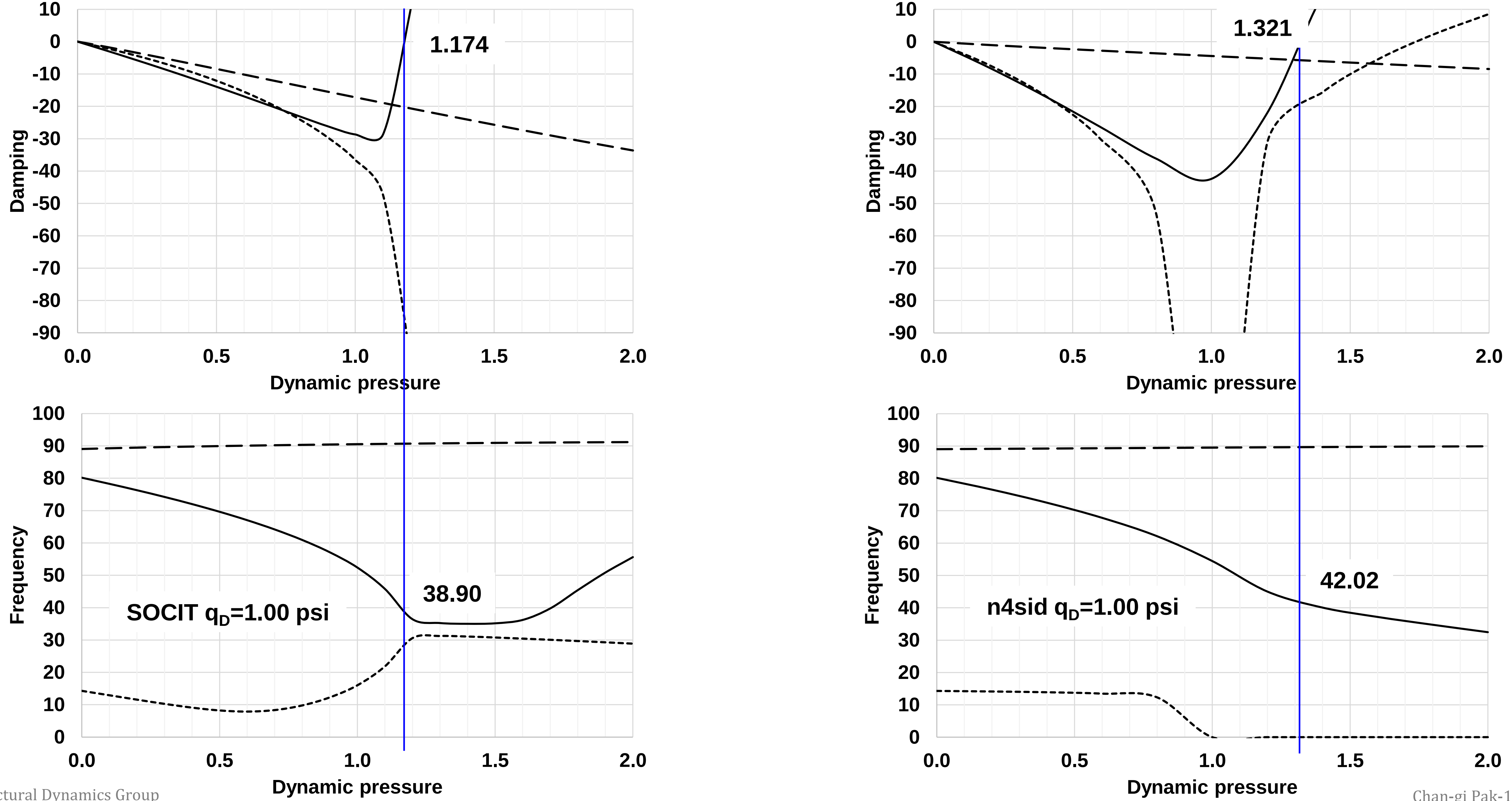




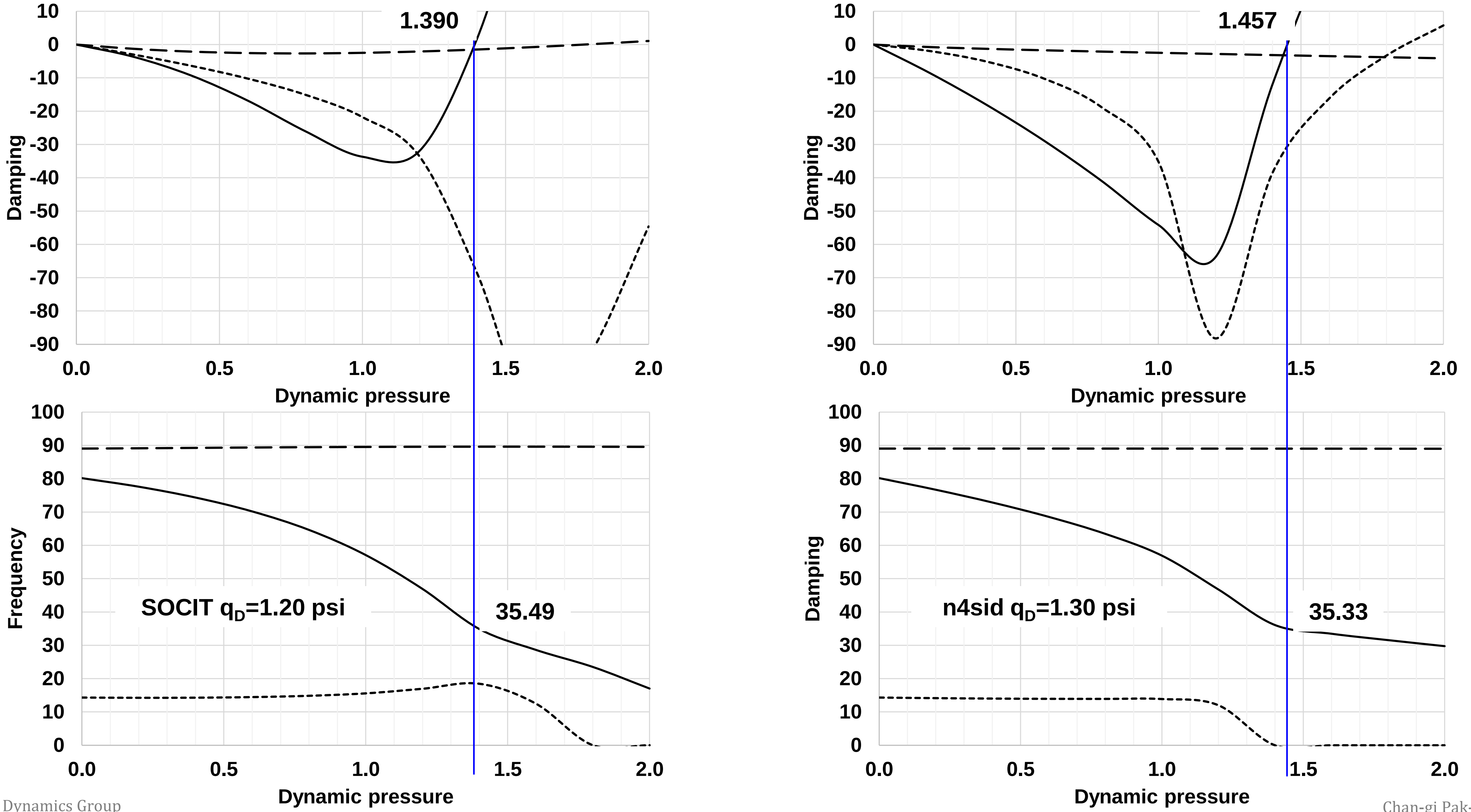




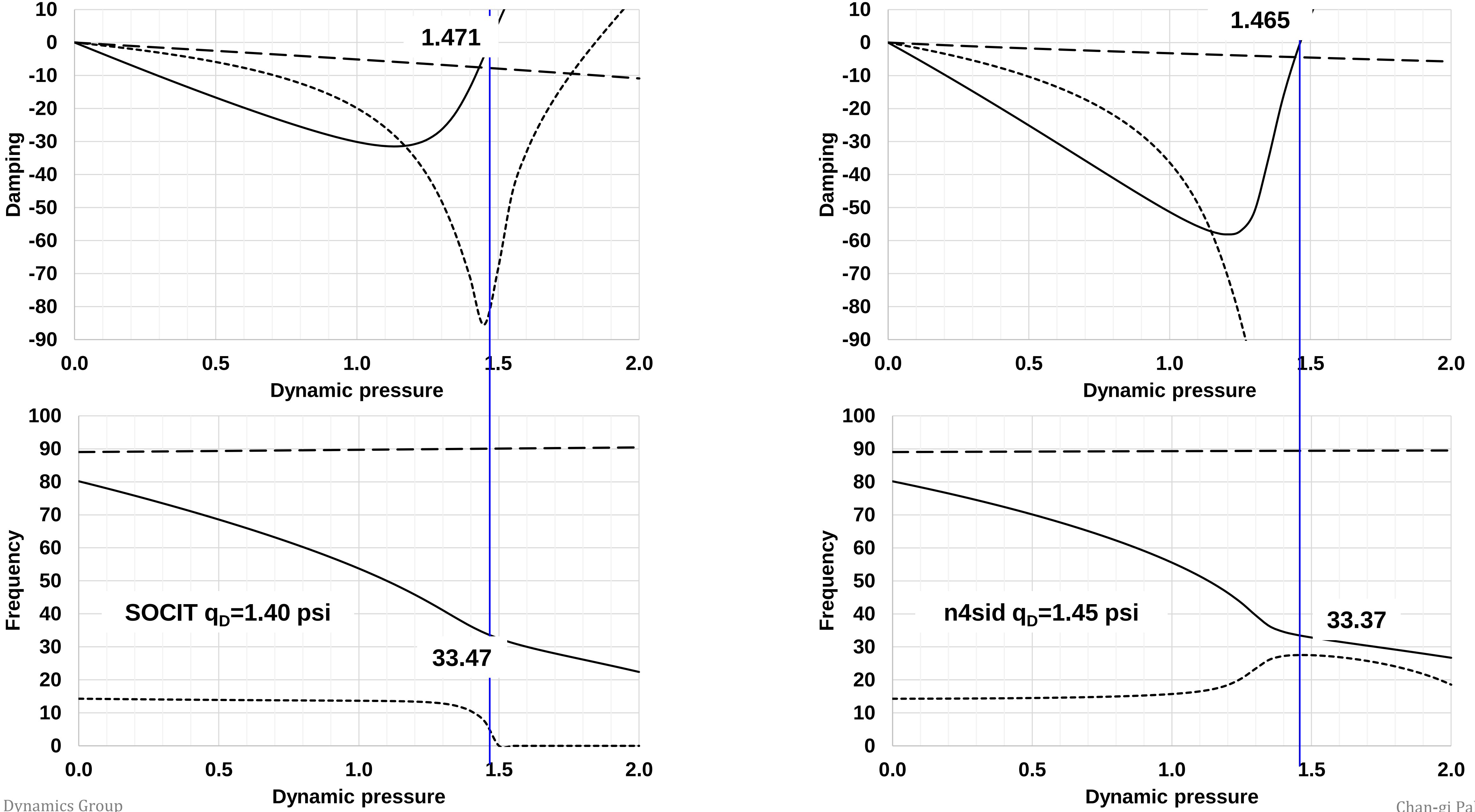
$(q_D - g)$ and $(q_D - f)$ plots for initial q_D = 1.0 psi



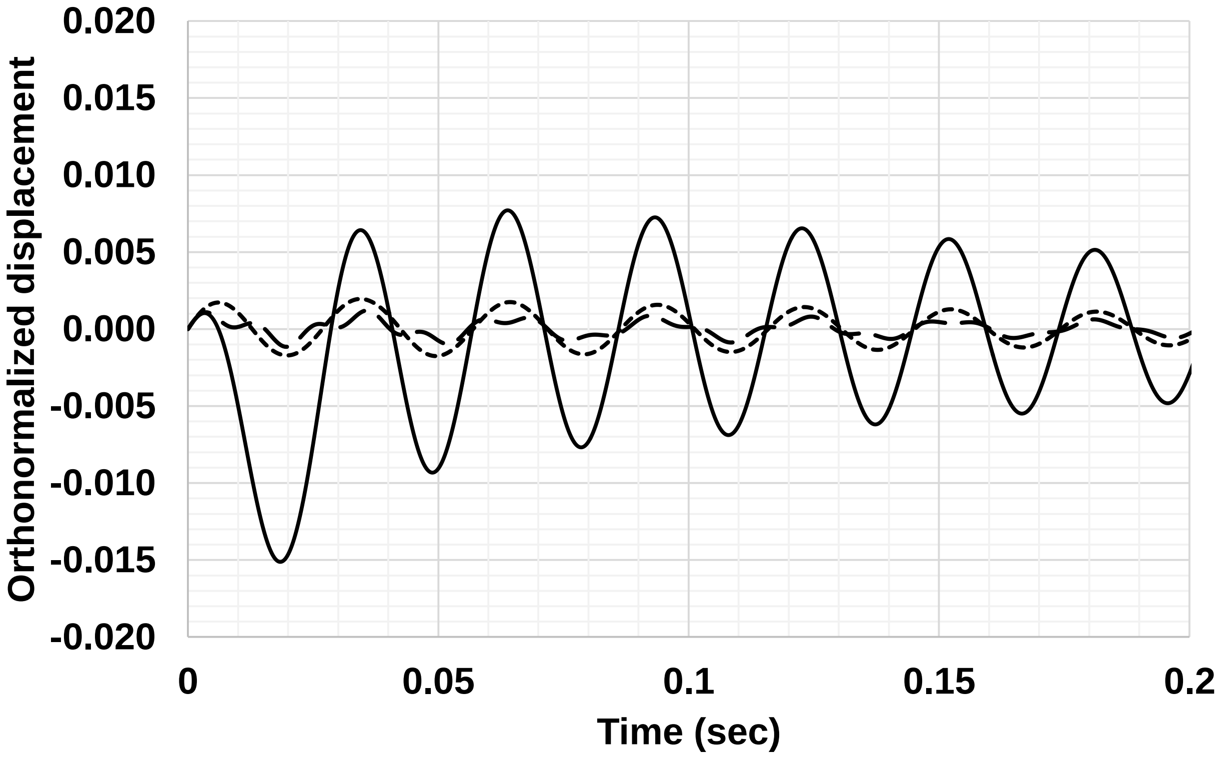
$(q_D - g)$ and $(q_D - f)$ plots for SOCIT (q_D = 1.20 psi) and n4sid (q_D = 1.30 psi)



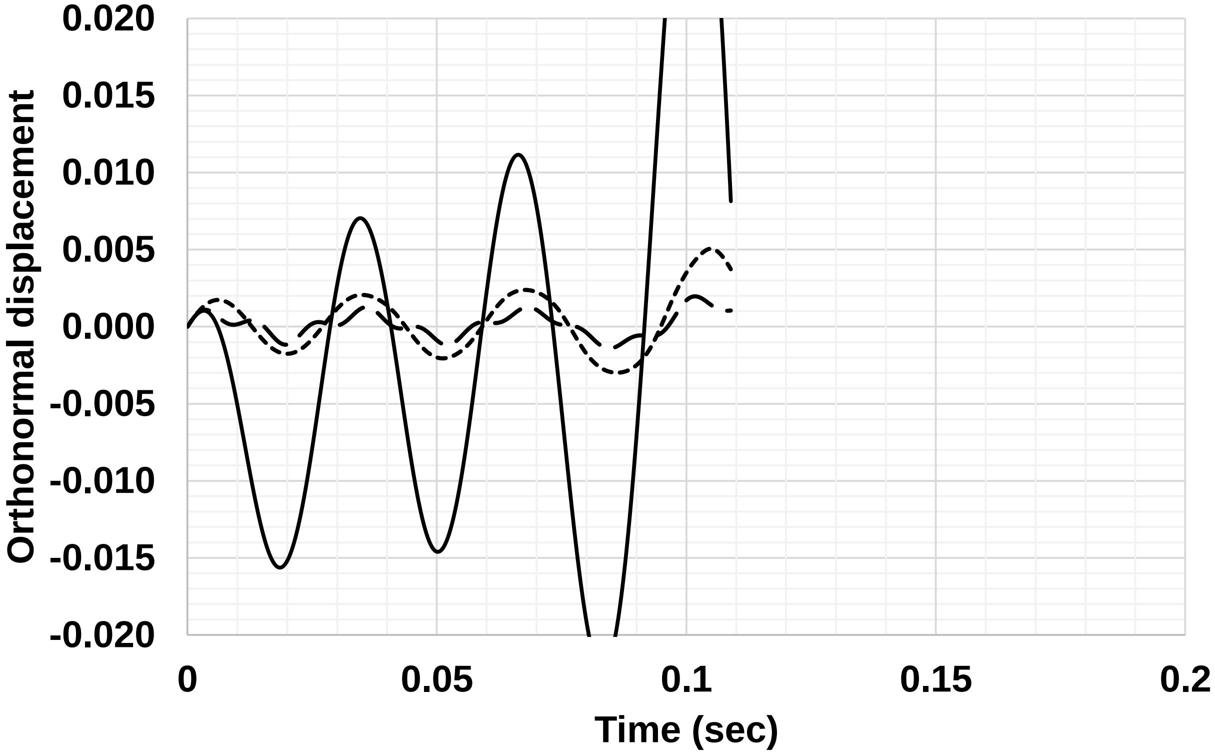
$(q_D - g)$ and $(q_D - f)$ plots for SOCIT (q_D = 1.40 psi) and n4sid (q_D = 1.45 psi)



Time histories of orthonormalized displacement with dynamic pressures of 1.45 and 1.46 psi

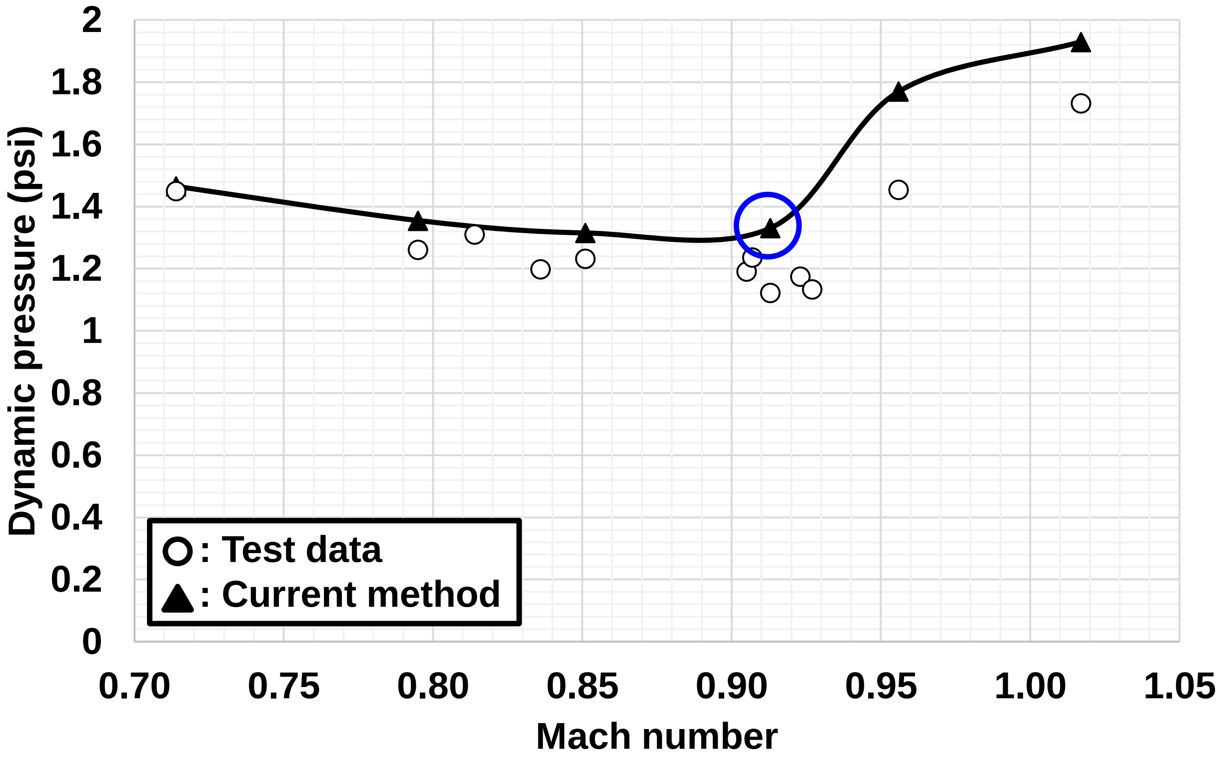


(a) q_D=1.45 psi

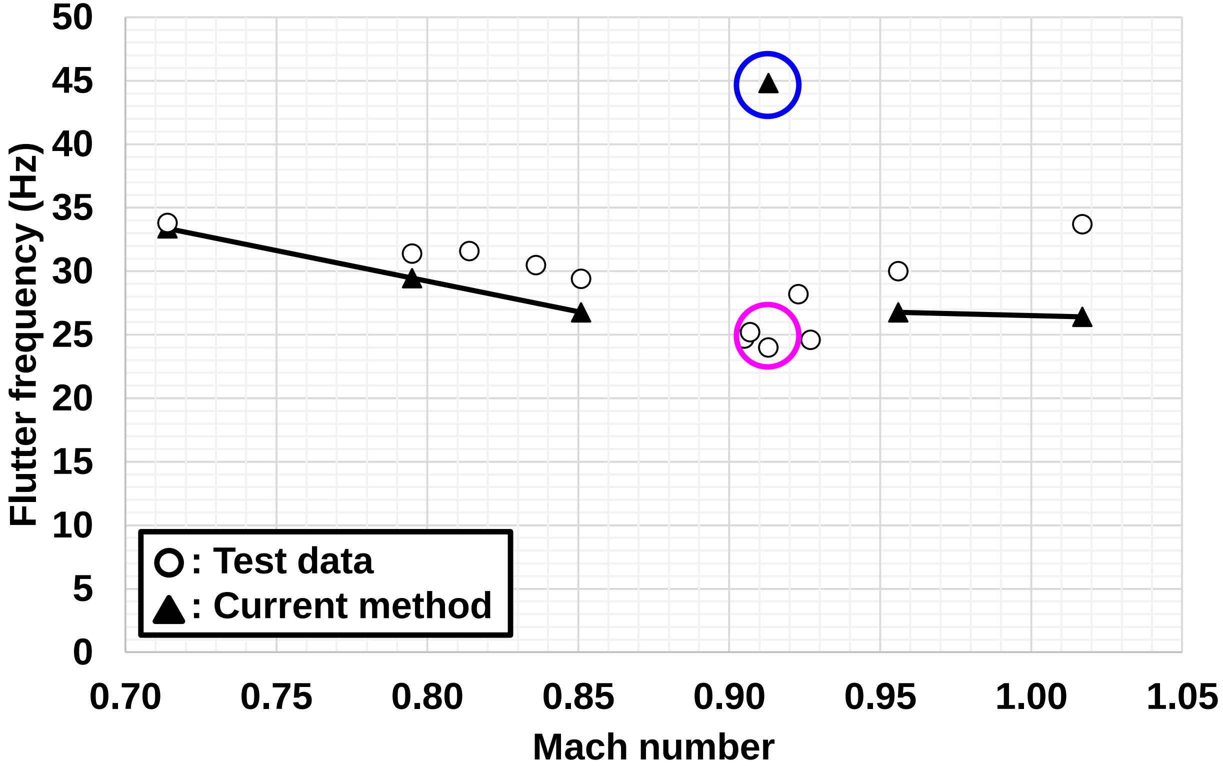


(b) q_D=1.46 psi

Flutter boundary of the cantilevered rectangular wing

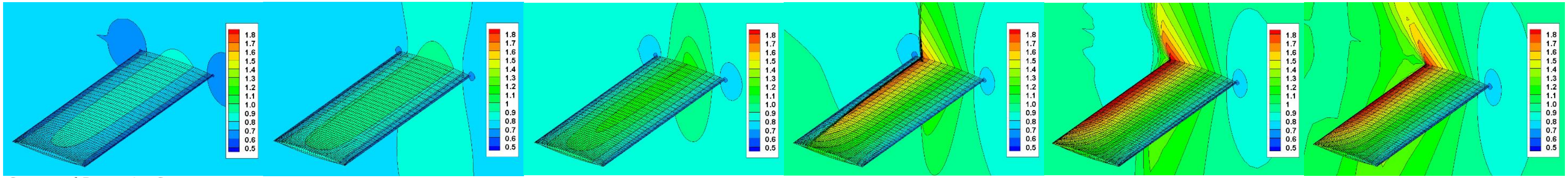


(a) Dynamic pressure

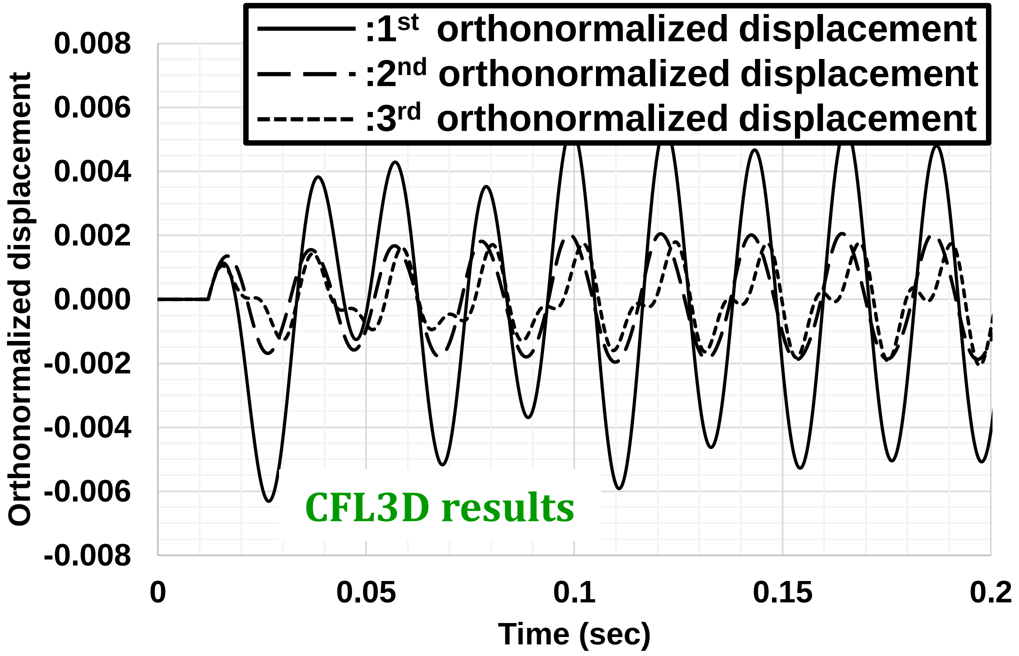


(b) Flutter frequency

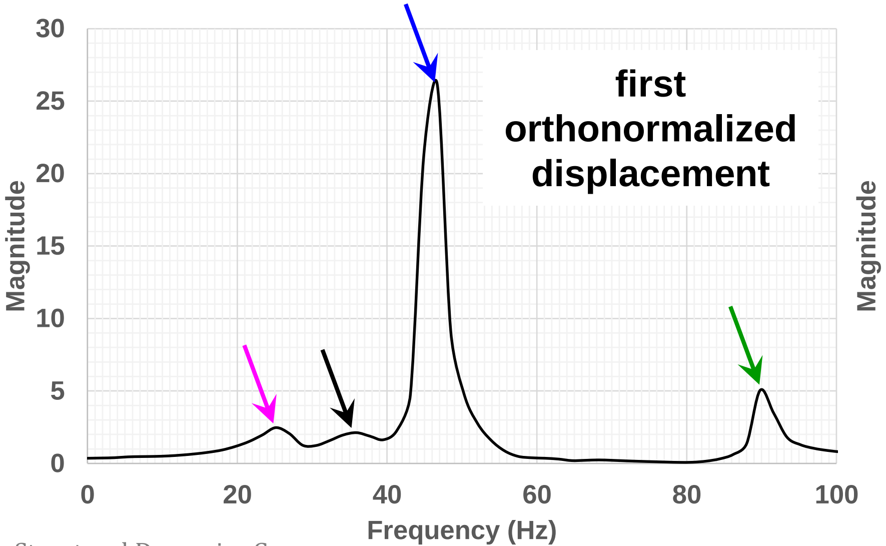
0.714 | 0.795 | 0.851 | 0.913 | 0.956 | 1.017

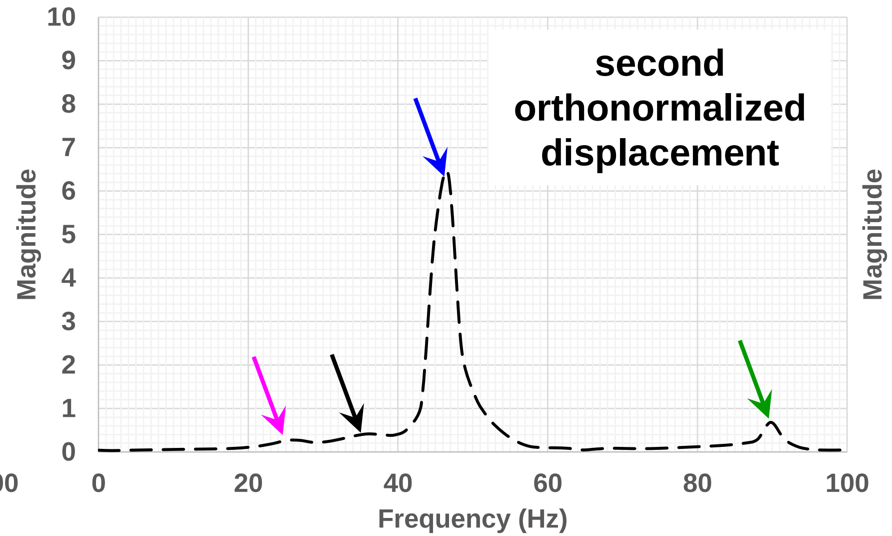


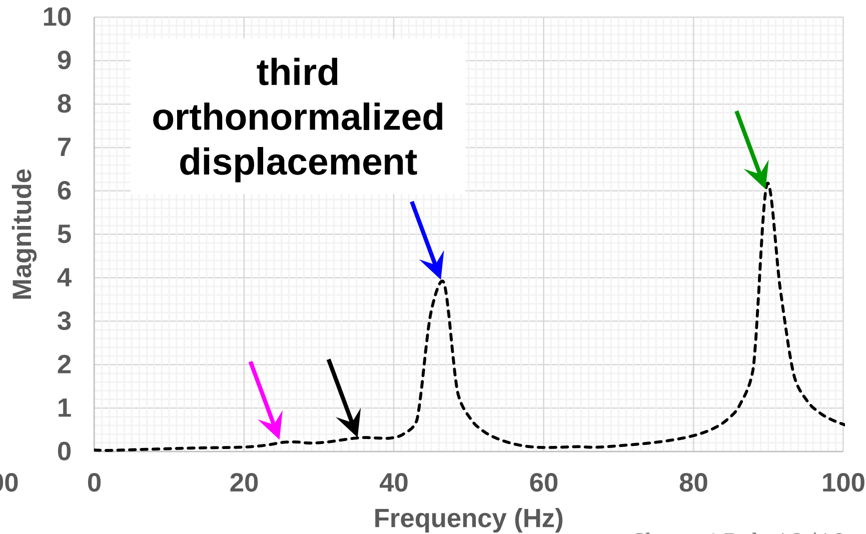
Time histories & PSDs of the first three orthonormal displacements



- 25Hz, 35Hz, **46Hz**, & 90Hz
- **CFL3D with Euler option** could not provide the correct orthonormalized displacement and force vectors with the **first three** structural dynamic modes.







Conclusions

- A new time-domain technique for computing flutter speed and frequency based on computational fluid dynamics (CFD) results was presented.
  - The **CFL3D v.6 code** with the **Euler option** was used for solving the 3-D flows on the structured grid.

- The full aeroelastic model is created by coupling the **estimated** aerodynamics model with the **known** structure dynamic model.
  - The proposed approach is successfully implemented to identify the flutter boundaries of a cantilevered rectangular wing model.
  - Computed flutter speeds and frequencies are in good match with measured quantities, however, the CFL3D code with the Euler option could not provide the correct orthonormalized displacement and force vectors with the first three structural dynamic modes in transonic speed regimes.

- Surface grids of the CFD model are **included** in the structural FE model.
  - These surface CFD grids are connected to the nearest structural finite element method grids using interpolation (**RBE3**) elements.
  - This proposed fitting technique between structural finite element and CFD models is successful.

- The most critical technology for the success of the proposed approach is the robust **MIMO parameter estimator.**

Questions ?